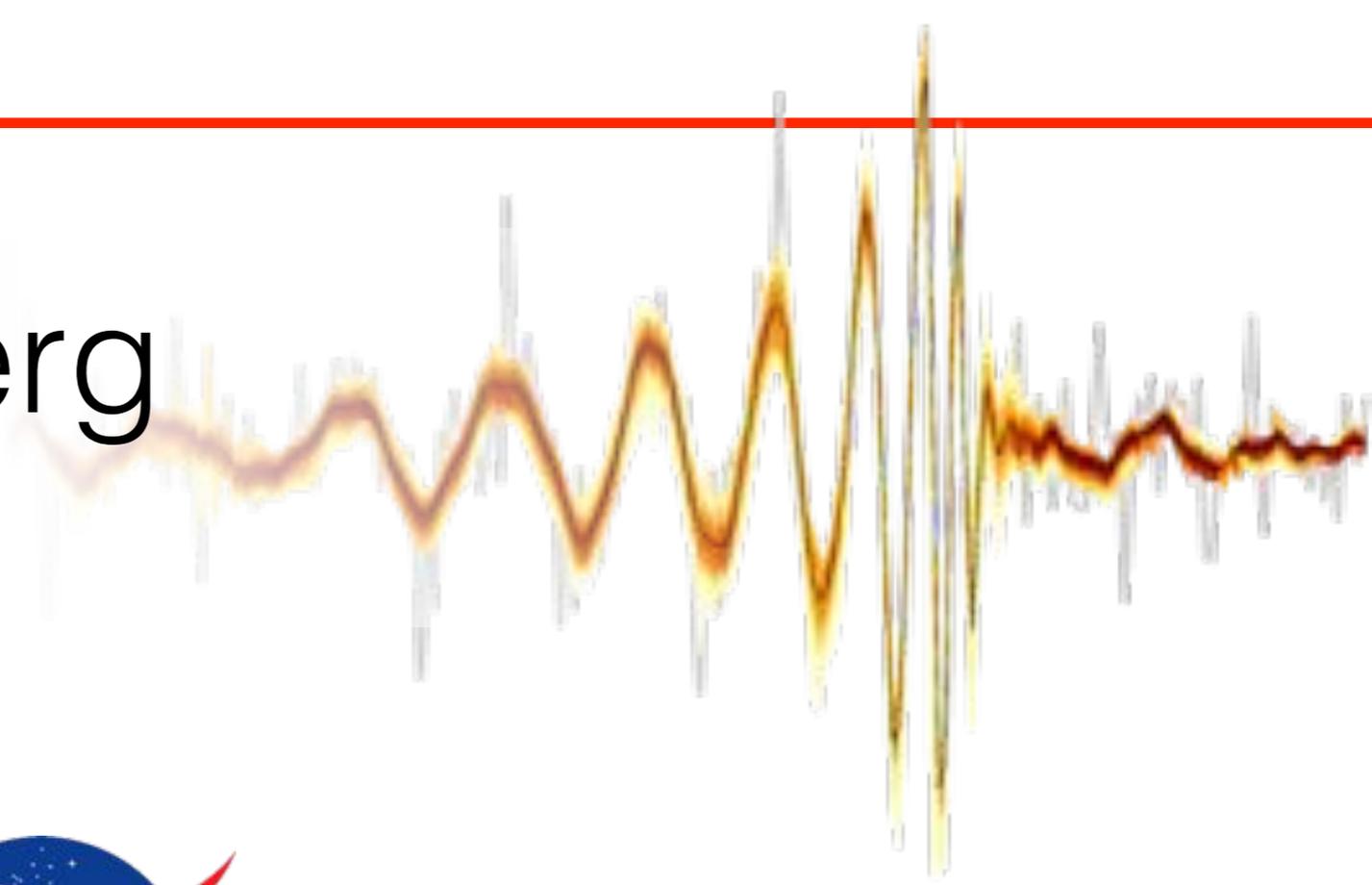


# Gravitational Wave Astronomy

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Tyson B. Littenberg

NASA/Marshall Space Flight Center













LIGO



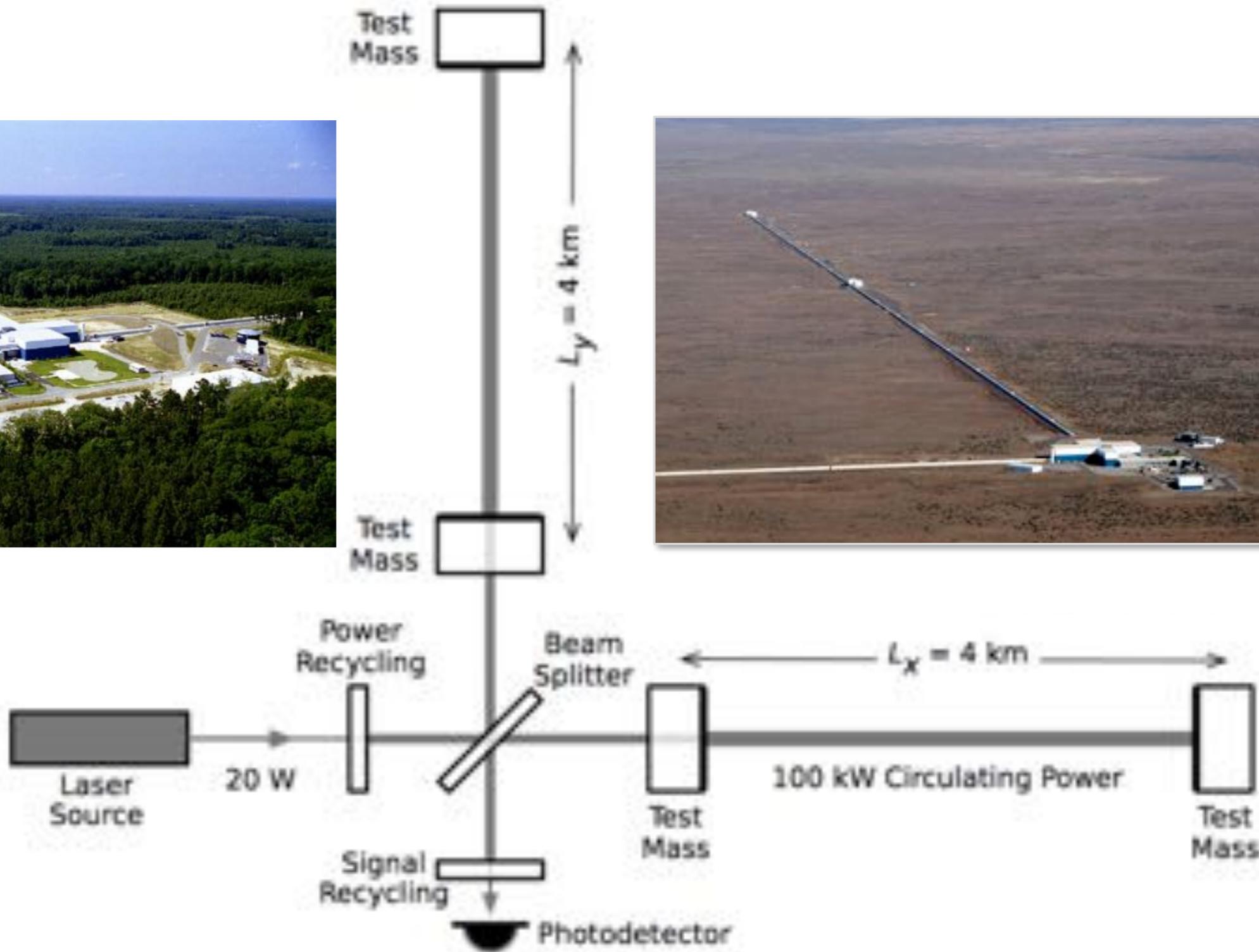
LASER

INTERFEROMETER

GRAVITATIONAL

WAVE

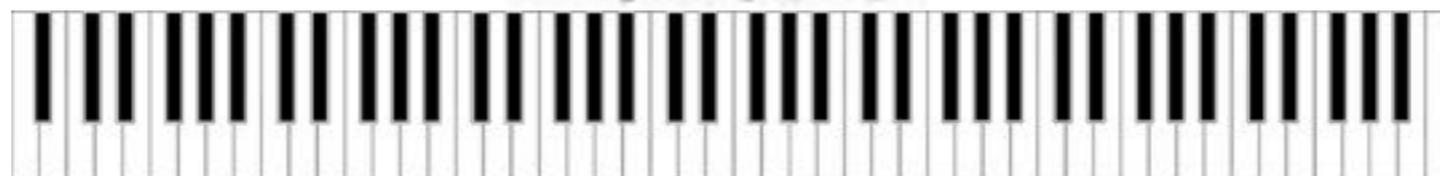
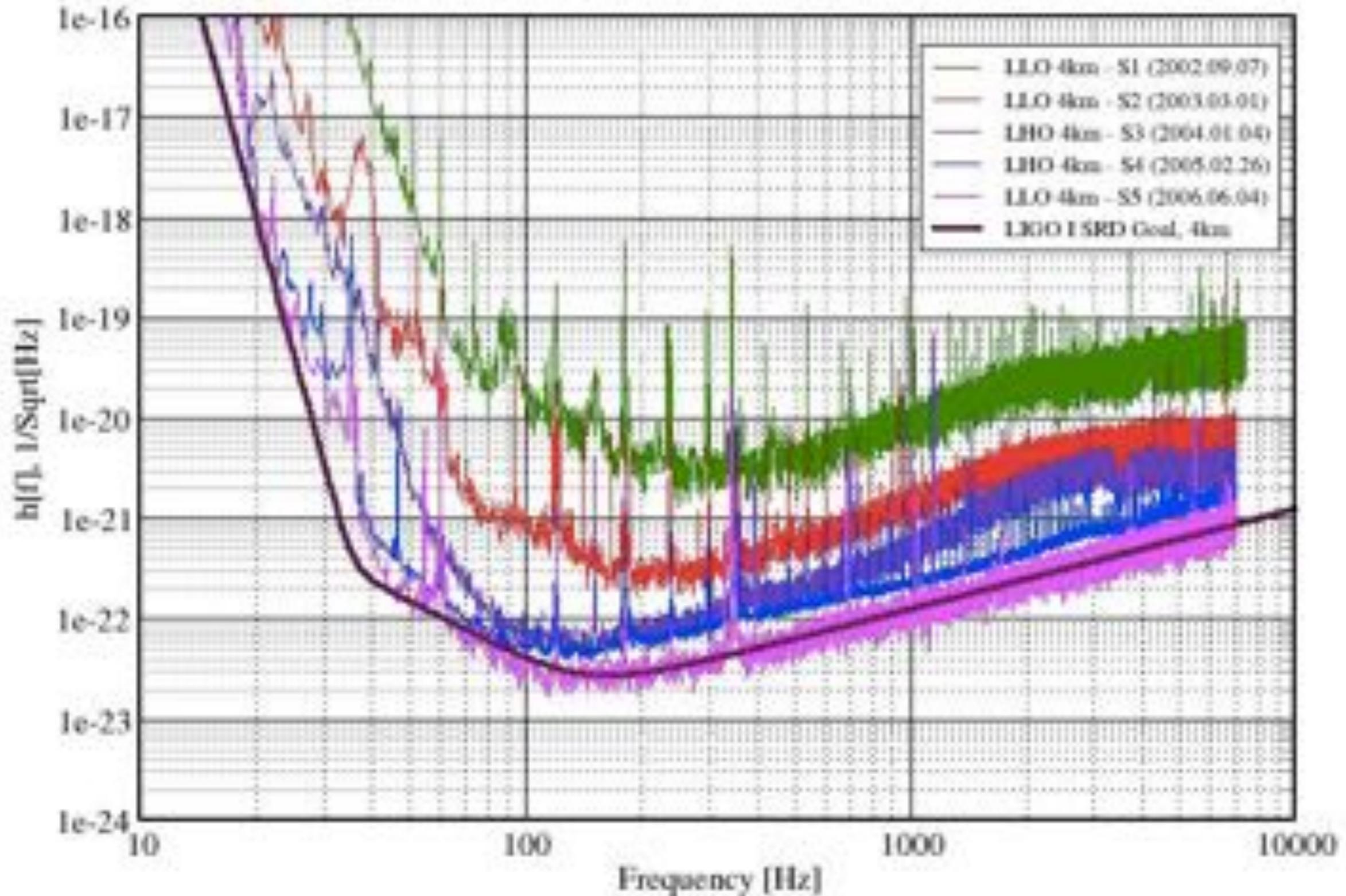
OBSERVATORY

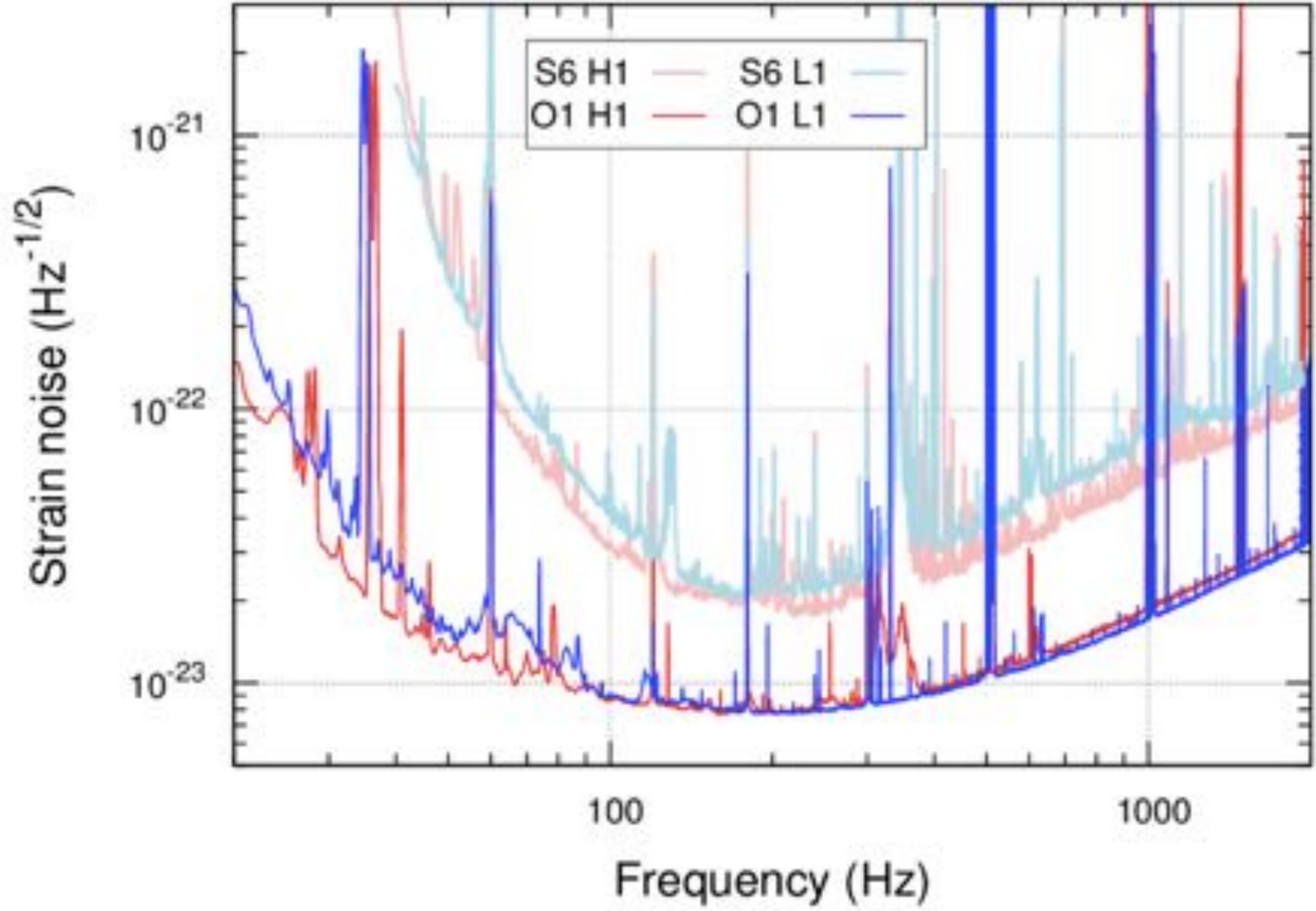




# Best Strain Sensitivities for the LIGO Interferometers

Comparisons among S1 - S5 Runs LIGO-G060009-02-Z

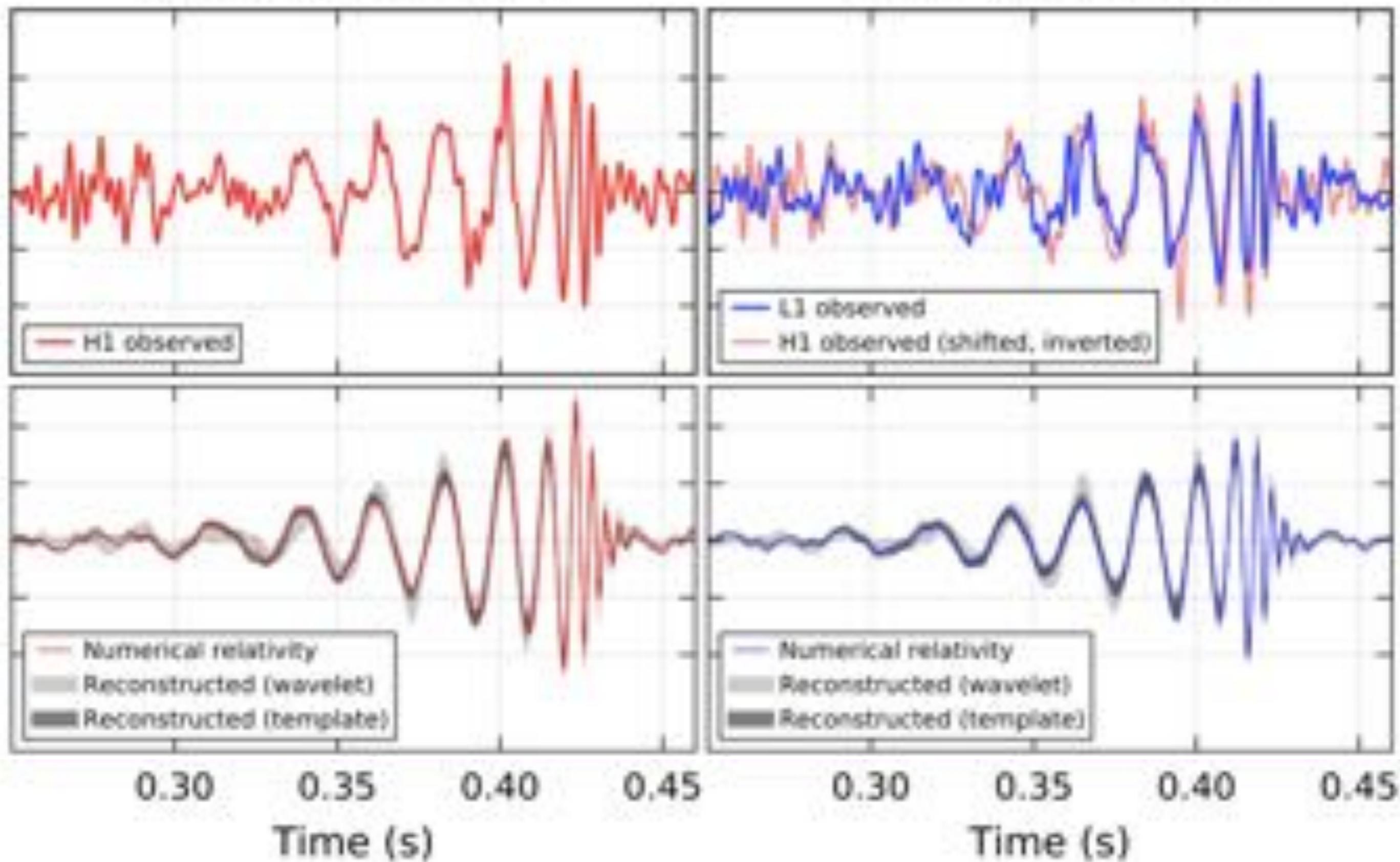


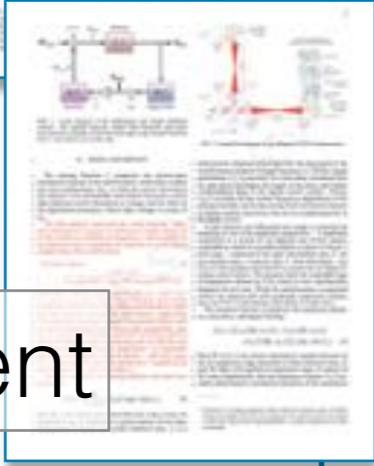
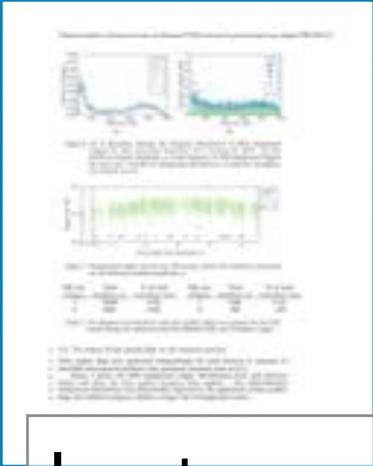
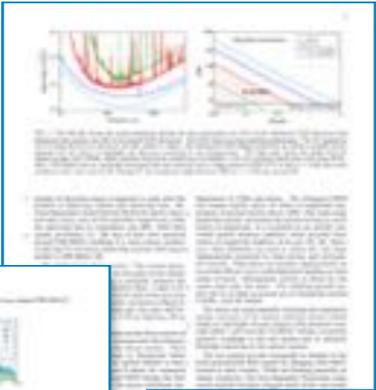
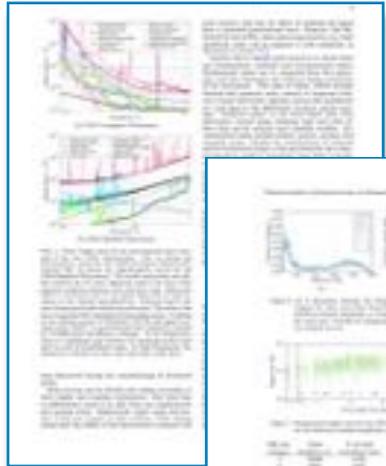




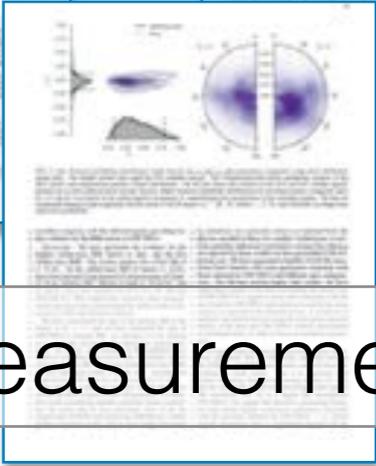
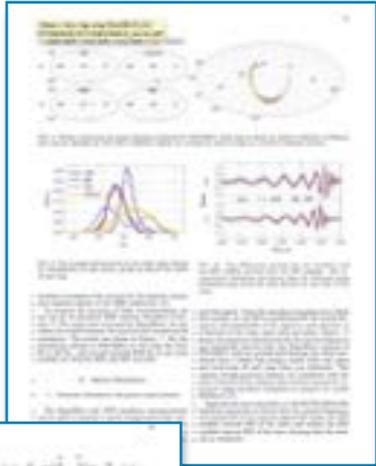
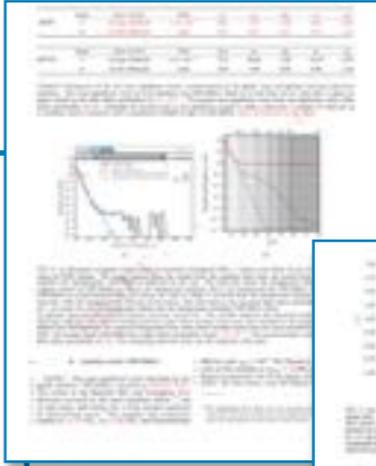
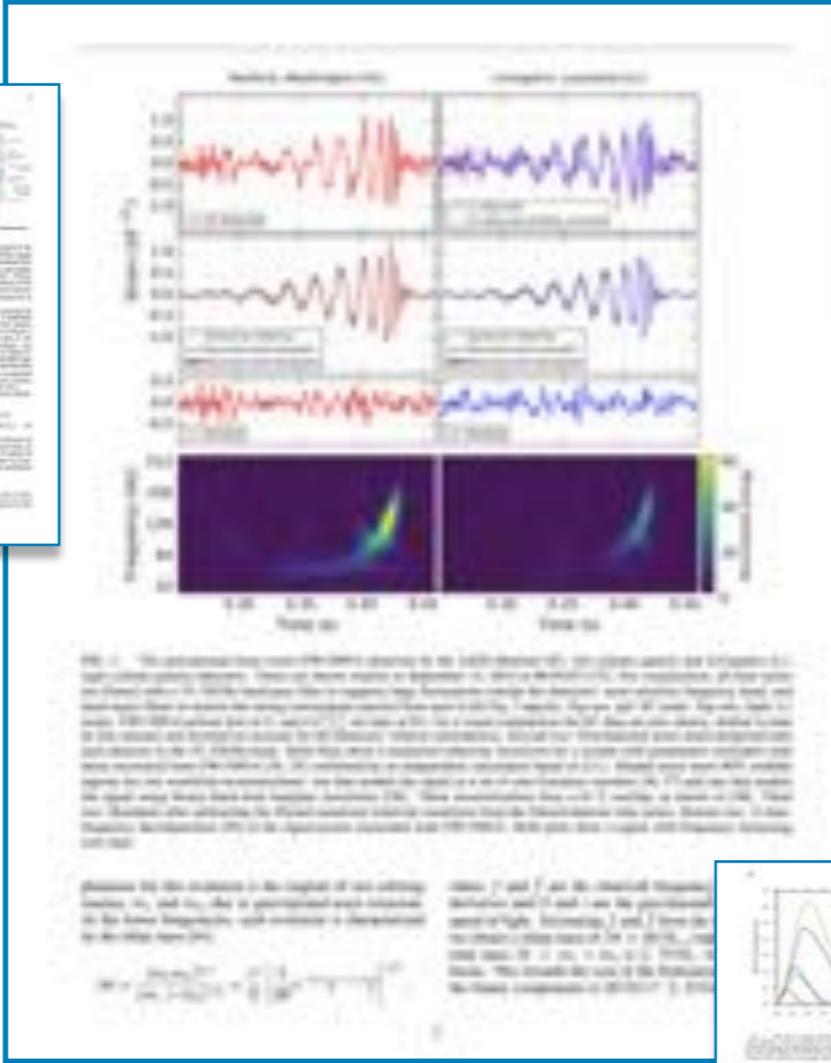
Hanford, Washington (H1)

Livingston, Louisiana (L1)

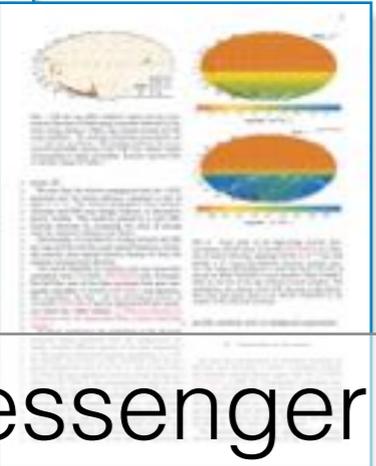
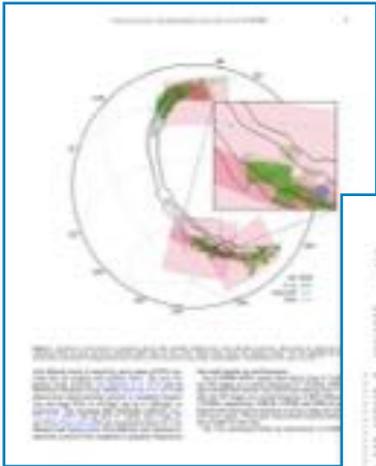




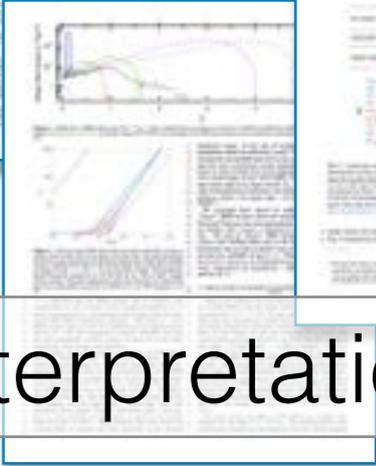
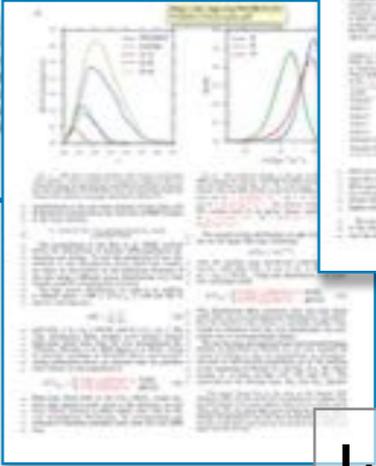
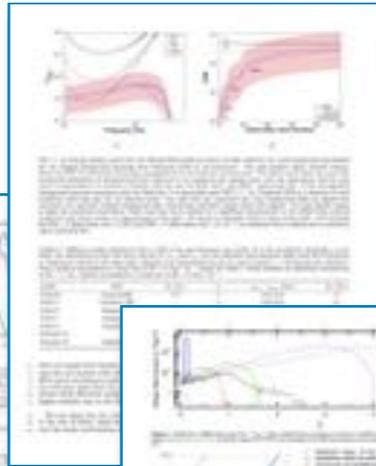
Instrument



Measurement



Multimessenger



Interpretation

**The Bakersfield Californian**  
 THURSDAY, FEBRUARY 24, 2011 11:00 AM BAKERSFIELD, CALIF. 93311

**MAKING WAVES**

**Lawsuit disputes union access to farms**

**500X** **4.30**

**The Huntsville Times**

**UAH 'AT THE CENTER' OF CONFIRMING EINSTEIN'S THEORY OF RELATIVITY**

**Huntsville ready to welcome Uber, Lyft and Zipcar**

**Lawmakers hold key to building mega-prisons**

**500X** **4,000 ON** **249**

**The Washington Post**

**U.S., Russia agree to a halt in Syrian war**

**Faculty line spotlighted in W. debate**

**U.S. House passes bill to fund Syria war**

**U.S. House passes bill to fund Syria war**

**The New York Times**

**U.S. House passes bill to fund Syria war**

**U.S. House passes bill to fund Syria war**

**U.S. House passes bill to fund Syria war**

**SANTA FE NEW MEXICAN**

**Deeper cuts needed to counter 'fisc cliff,' Smith says**

**With faint chirps, scientists prove Einstein correct**

**LANL crew had faith discovery was matter of time**

**Measure to alter Army scholarship funding advanced**

**People's Choice**

**LISTENING TO A WINTERWONDERGRASS**

**THE DENVER POST**

**"The skies will never be the same."**

**Ch. 11 may let chain play ball**

**EPH employees will be aware of changes of state Normal**

**Surprise Valentine's Day** **KING**

**The Gazette**

**Edged in the end at Indiana**

**Cricket Hollow Zoo visitations 'pervasive,' judge finds**

**Einstein was right**  
 And here's why it matters

**God's escape from recent past could prompt changes in procedure**

**The Boston Globe**

**Rivals debate their support for Obama**

**A whisper from across the universe**

**Deal set for trace, aid drops in Syria**

**Parents sue nurse after 17-month-old's murder case**

**With focus of film, a structural problem**

**SLEEPYS**  
 Doorbusters 6 Hours Only!

**The Bakersfield Californian**  
FRIDAY, FEBRUARY 12, 2016 • BAKERSFIELD.COM

**MAKING WAVES** Gravitational waves, that is: New scientific observation affirms Einstein's general theory of relativity  
USA TODAY | 30

**Lawsuit disputes union access to farms**  
Practice-related laborers' constitutional protection, challenge claims, if successful, will could hamper efforts by United Farm Workers to connect with ag laborers  
USA TODAY | 2

**At Democratic debate, Sanders, Clinton spar over plans for change**  
USA TODAY | 28

**Wanted 'Deadpool,' starring Ryan Reynolds, onlook at the chaffers and**  
USA TODAY | 28

Bakersfield High captures 10th straight

**The Huntsville Times**

**UAH 'AT THE CENTER' OF CONFIRMING EINSTEIN'S THEORY OF RELATIVITY**

Huntsville ready to welcome Uber, Lyft and Zipcar

Lawmakers hold key to building mega-prisons

**The Washington Post**

**U.S., Russia agree to a halt in Syrian war**

Ex-will's tip led to gunfire at Md. Plaza

Fault line spotlighted in Wis. debate

Oregon siege ends as four surrender

Gravitational waves

**The New York Times**

**U.S., Russia agree to a halt in Syrian war**

Long in Chinese Courts, Black Notice Served

Lawyer in Charge of Benghazi & Ground War

**WEEKEND UPDATE: VON MILLER**

The Denver Broncos linebacker and Super Bowl MVP discusses the discovery of gravitational waves.  
(Season 45, 2016)

[MORE INFO](#)



**Measure to alter lottery scholarship funding advances**

**As more wash ashore, severed feet pose mystery in Pacific Northwest**

**Passapick**

**Surprise your loved one this Valentine's Day**

**WING CHANG**

Let Your Heart Skip a Beat on your Valentine!

**Einstein was right**

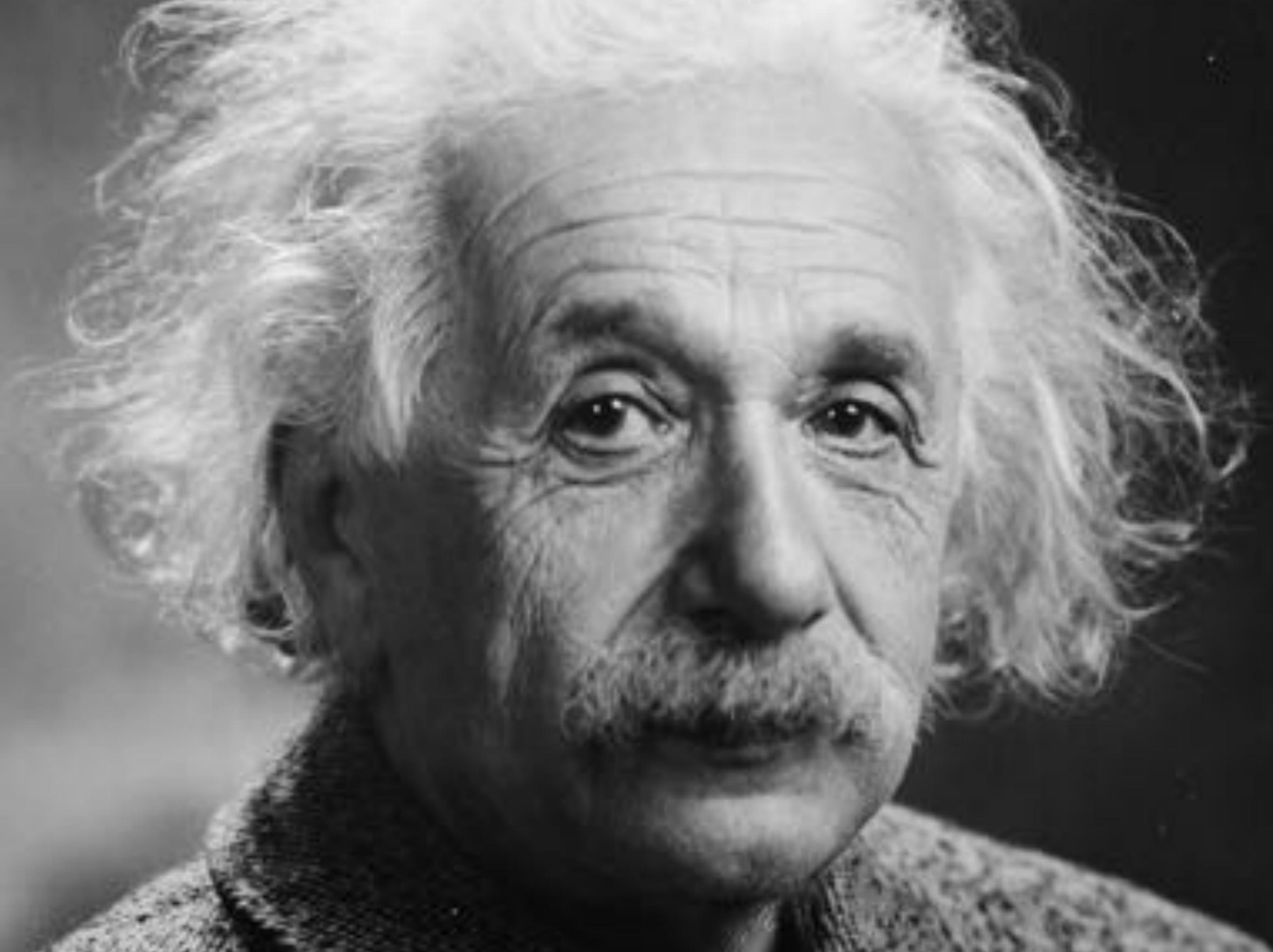
And here's why it matters

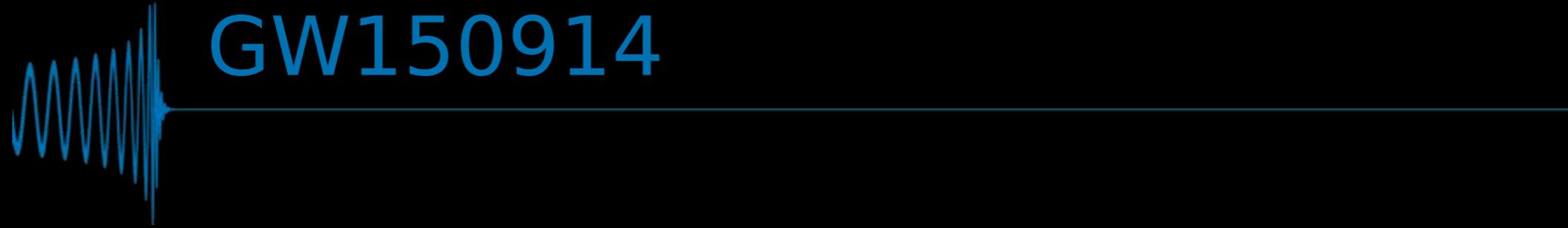
Goal's escape from research park could prompt changes in procedure

**With flurry of data, a no-school predictor**

**DA abandons murder case**

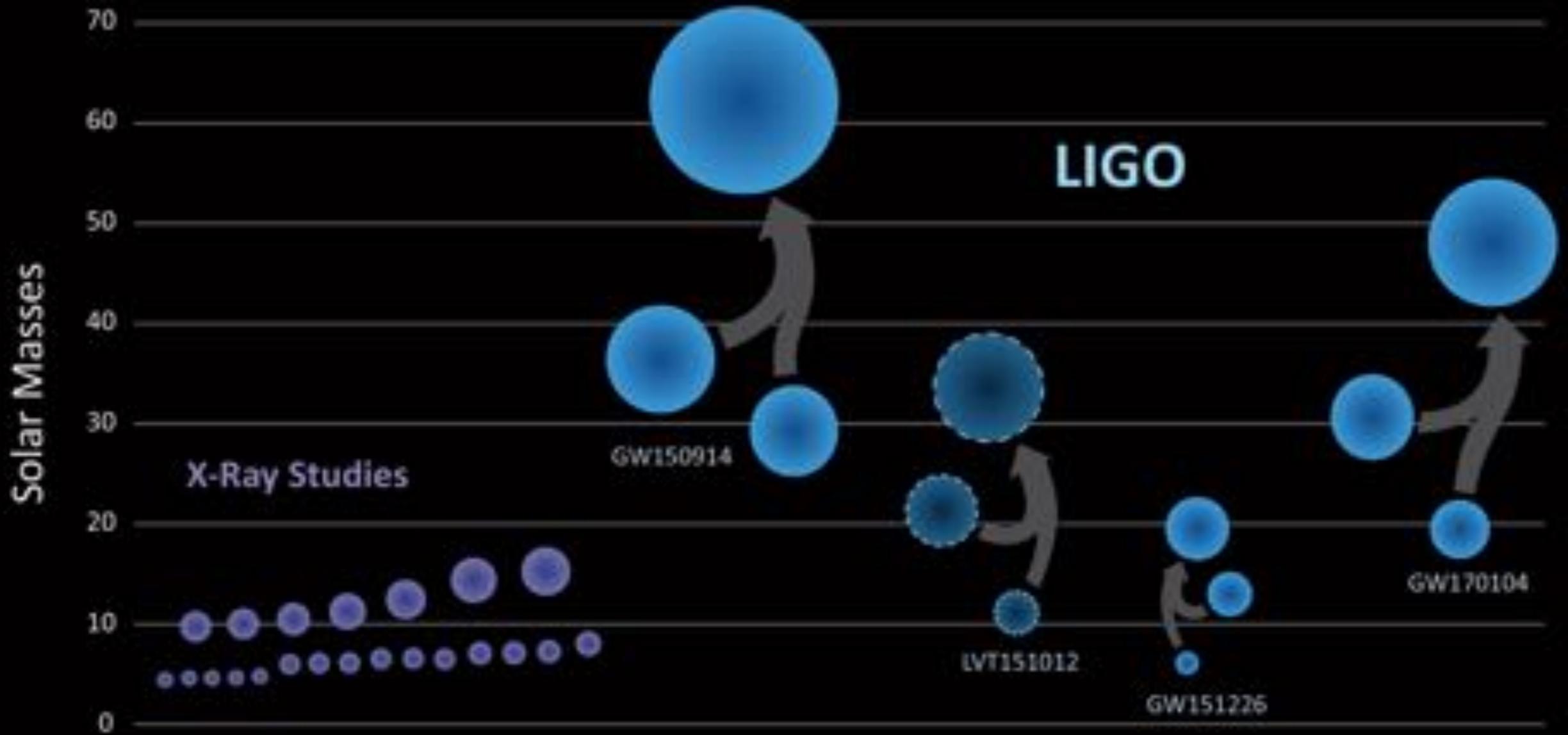
**SLEEPYS**  
The Mattress Professionals  
Doorbusters 6 Hours Only!  
SATURDAY 10AM-4PM





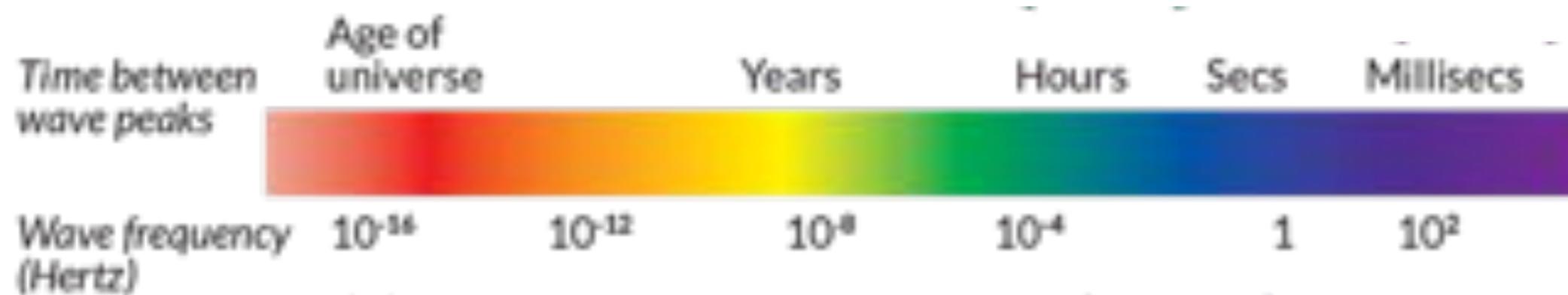
time observable by LIGO

# Black Holes of Known Mass

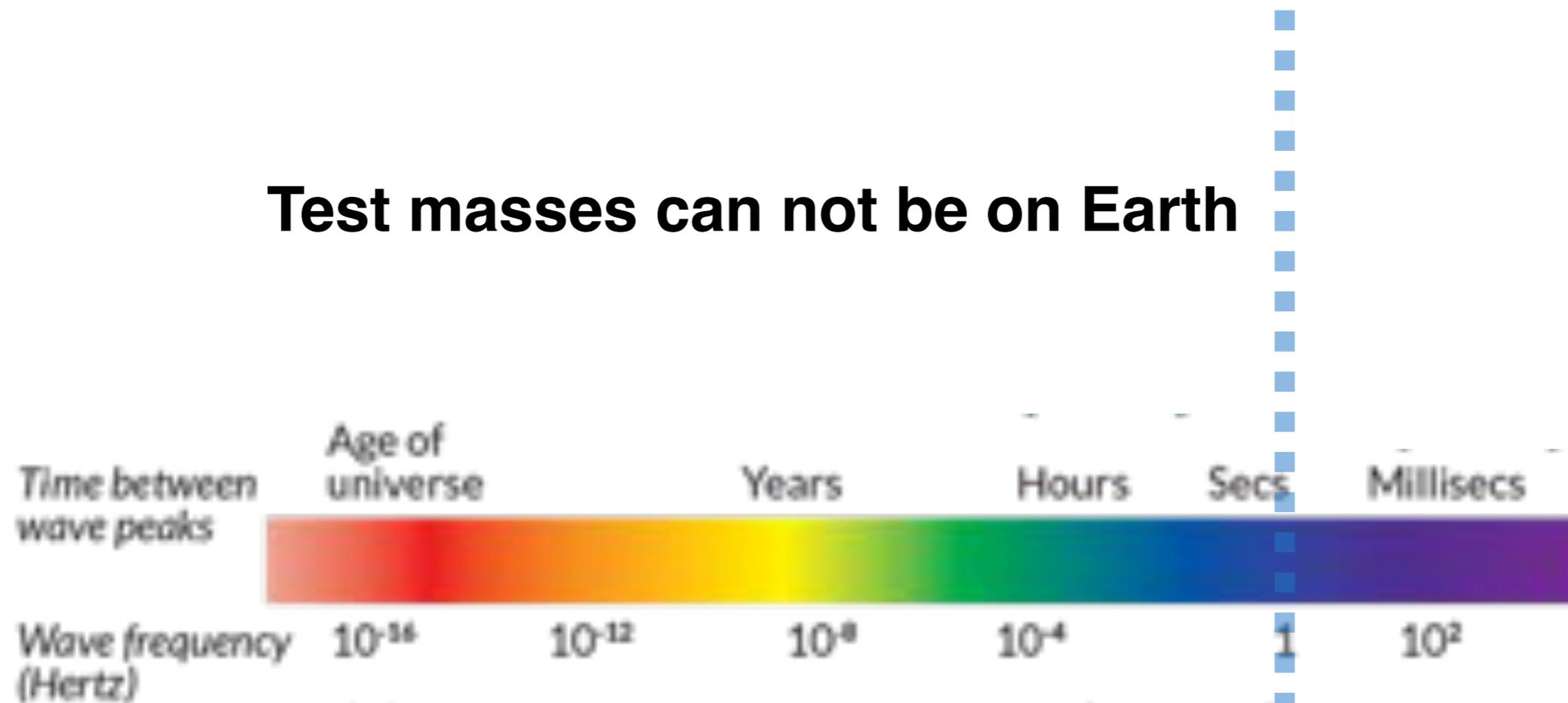




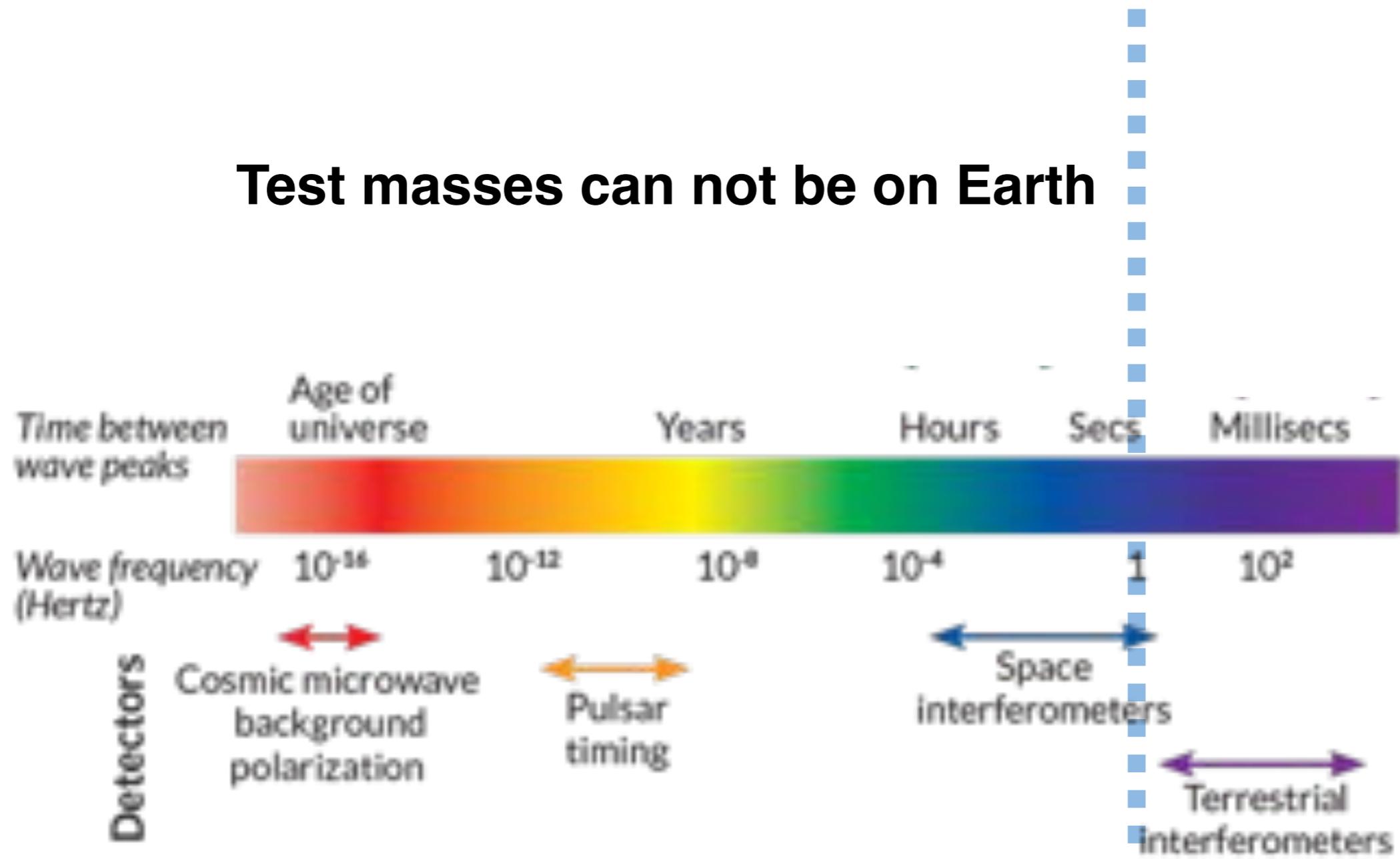


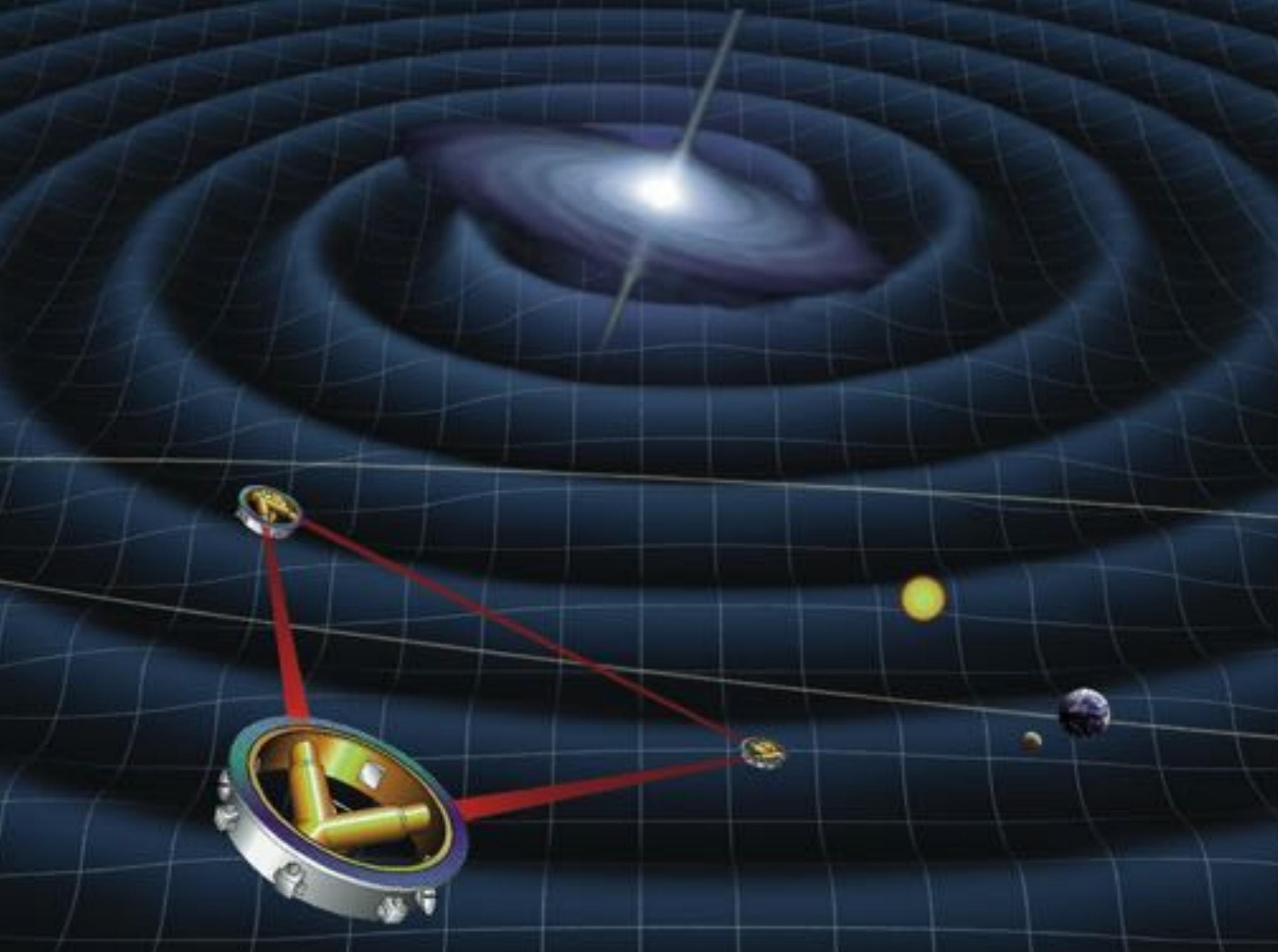


# Test masses can not be on Earth

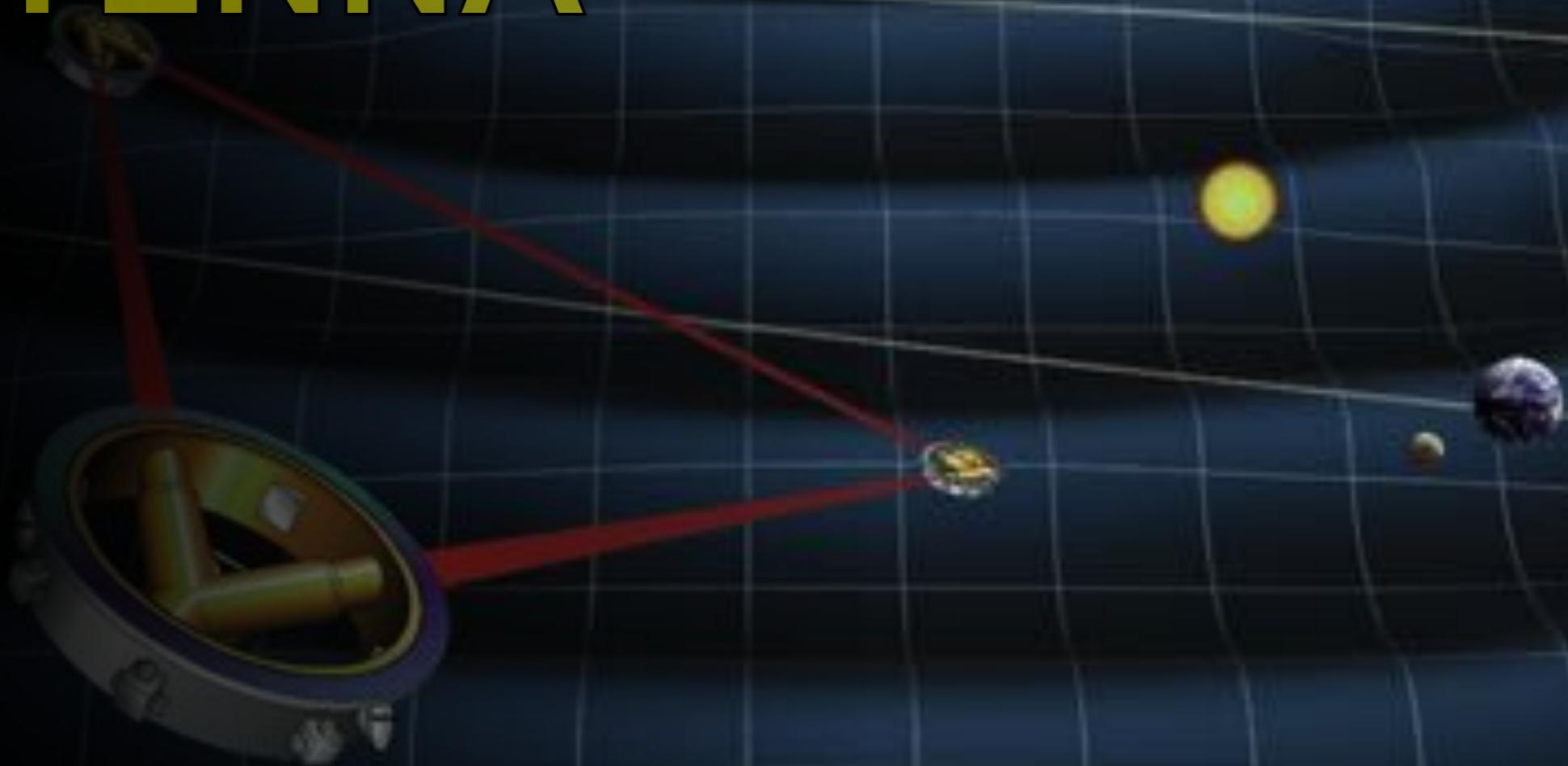
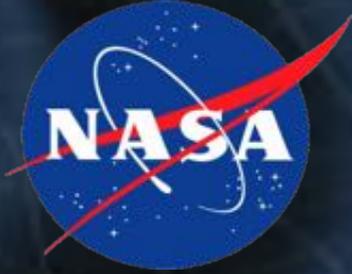


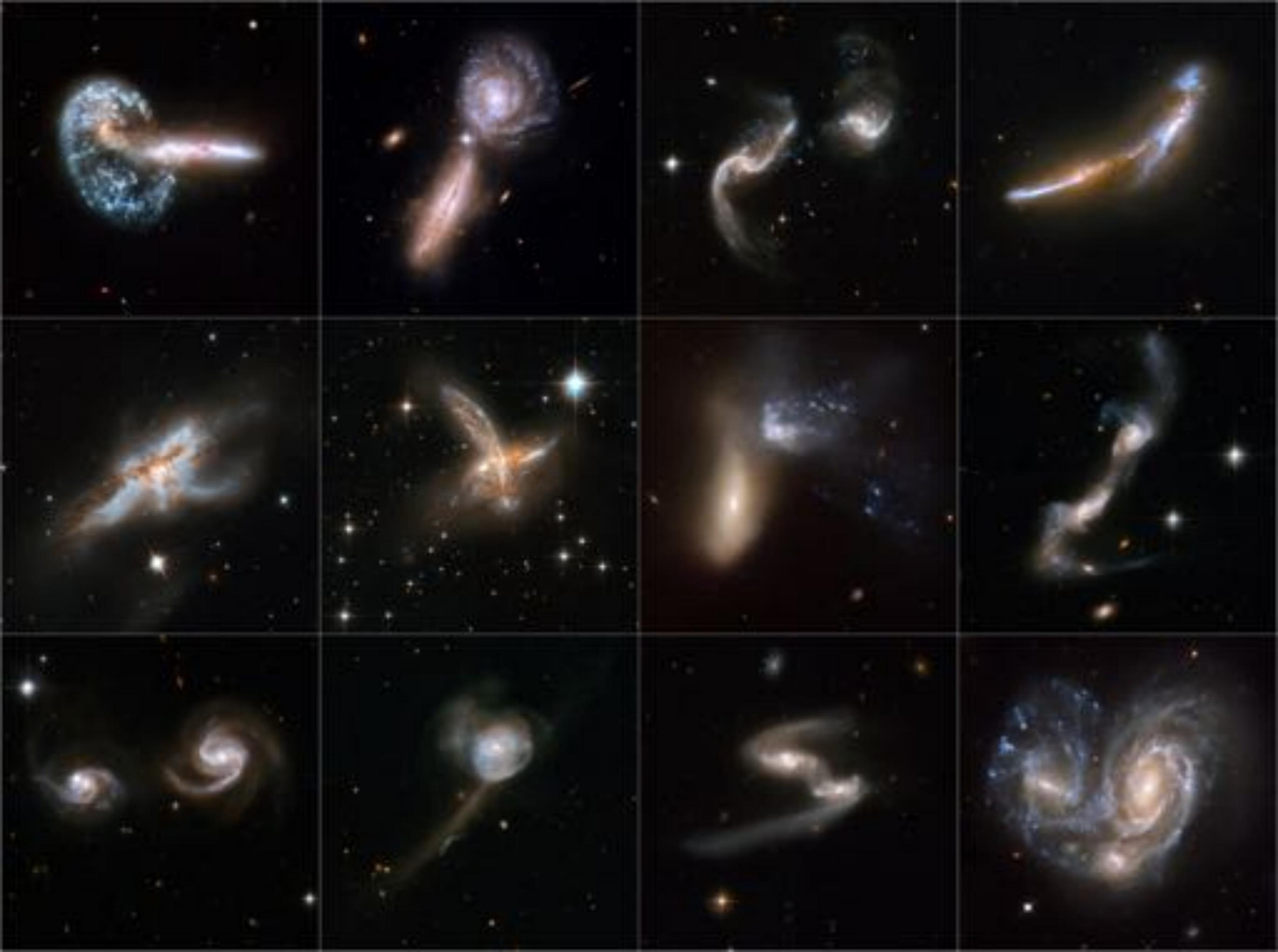
# Test masses can not be on Earth





# LASER INTERFEROMETER SPACE ANTENNA







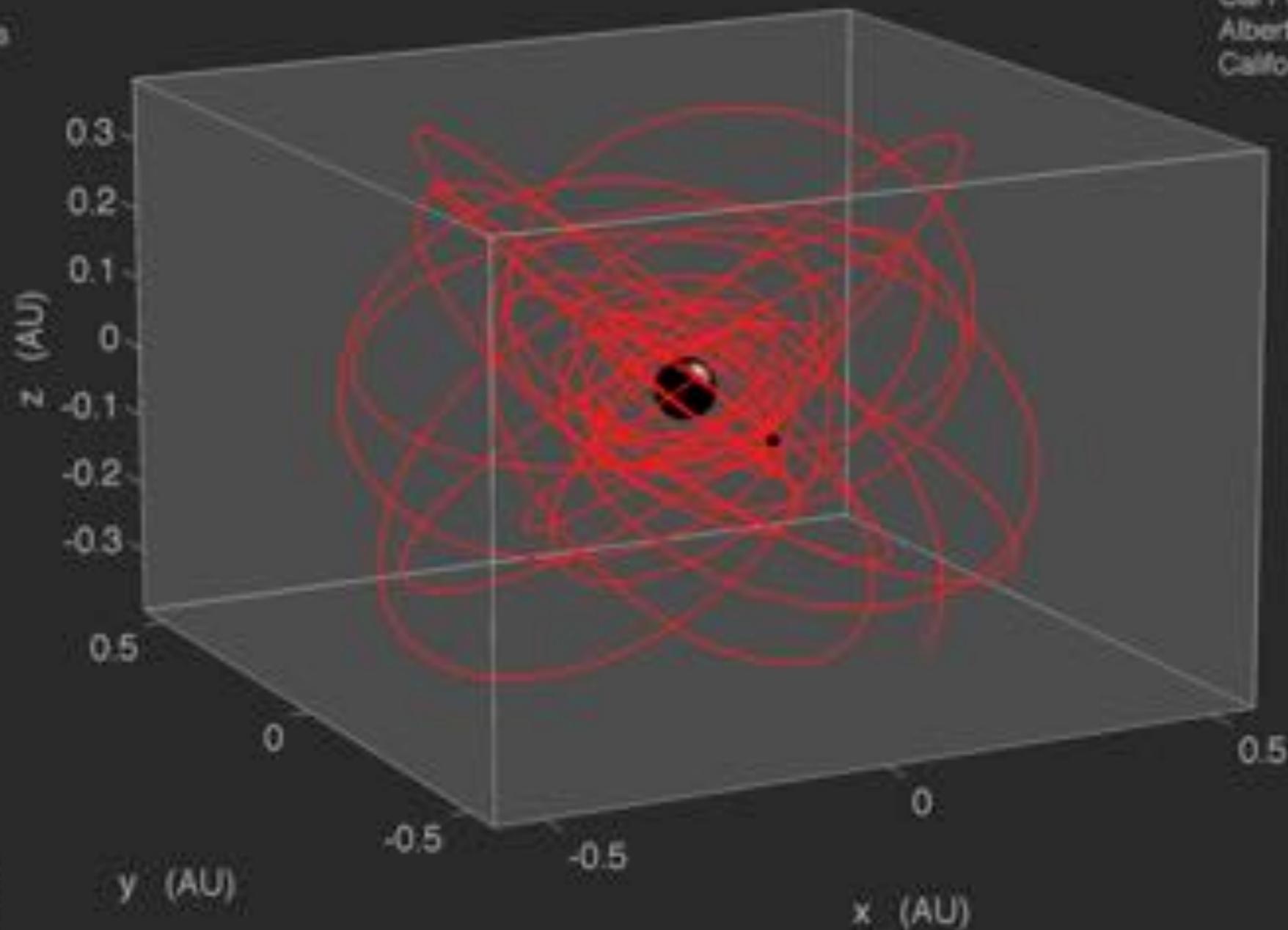
100 days before merger, 28% of light speed

Steve Drasco  
Cal Poly, San Luis Obispo  
Albert Einstein Institute  
California Institute of Technology

Large black hole:  
shown to scale  
3,000,000 solar masses  
90% maximal spin

Small black hole:  
shown enlarged  
270 solar masses  
negligible spin

Trace duration  
1 day



"plus" waveform viewed  
from 45 degrees latitude



Scale = 0 kpc



# LISA Pathfinder



Image: ESA/ATG Medialab

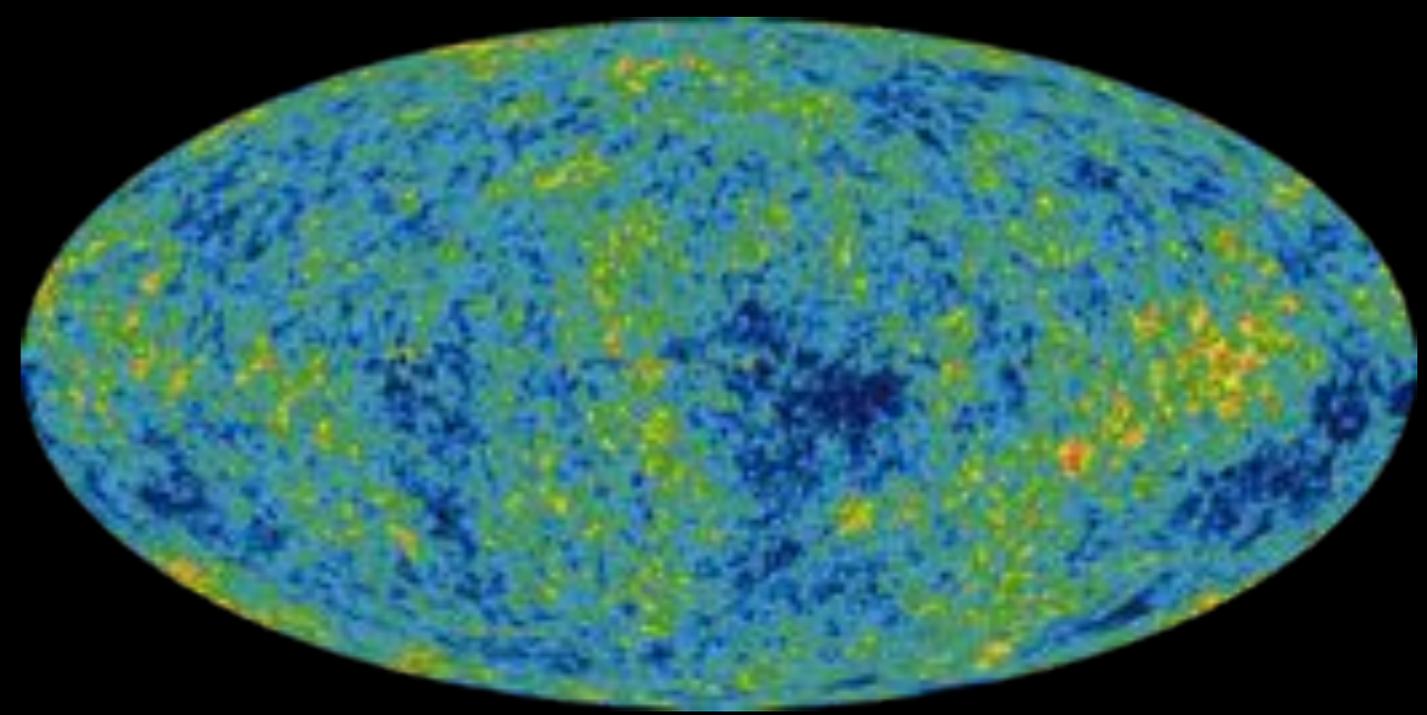


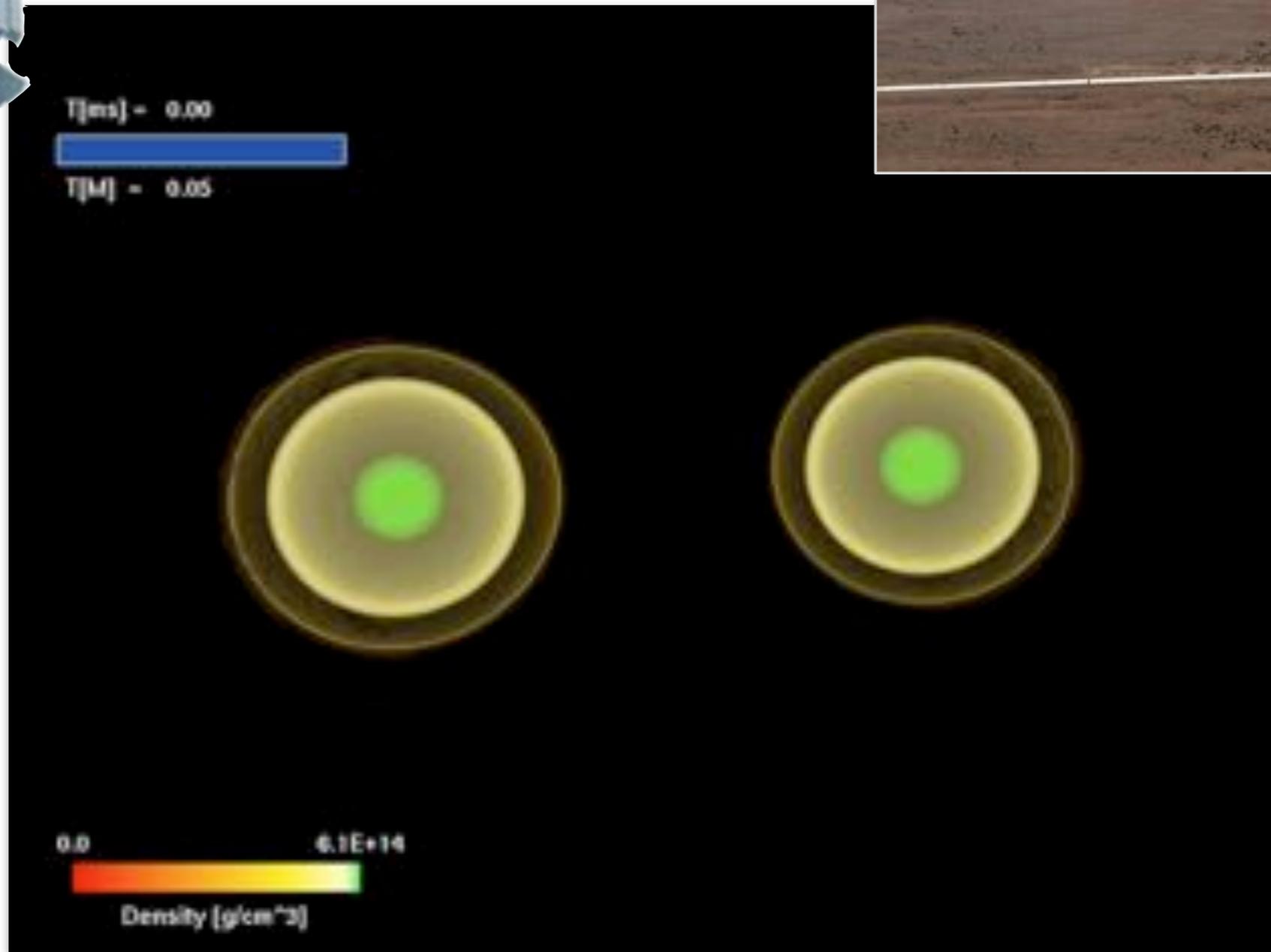
Image: ESA

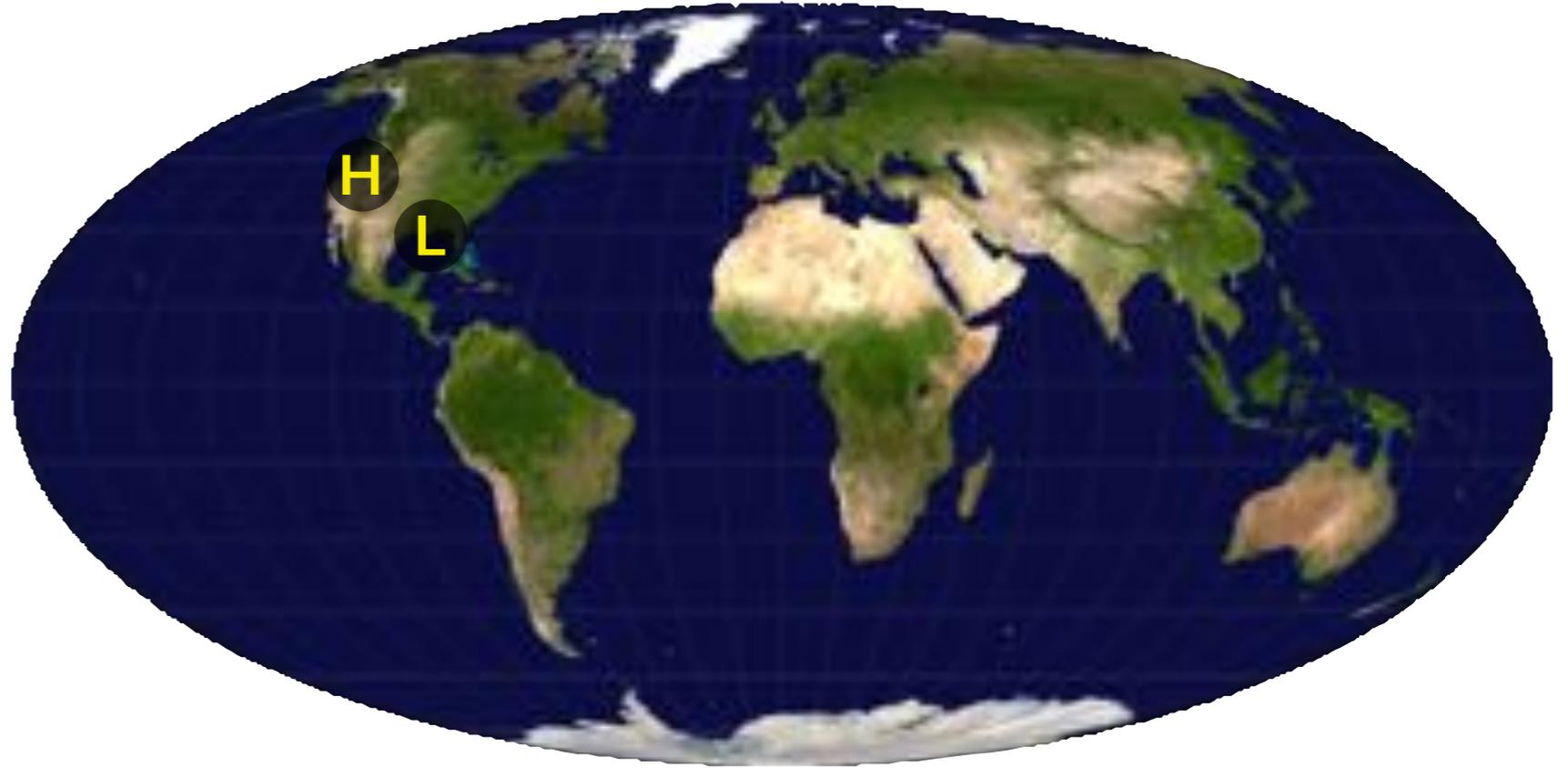


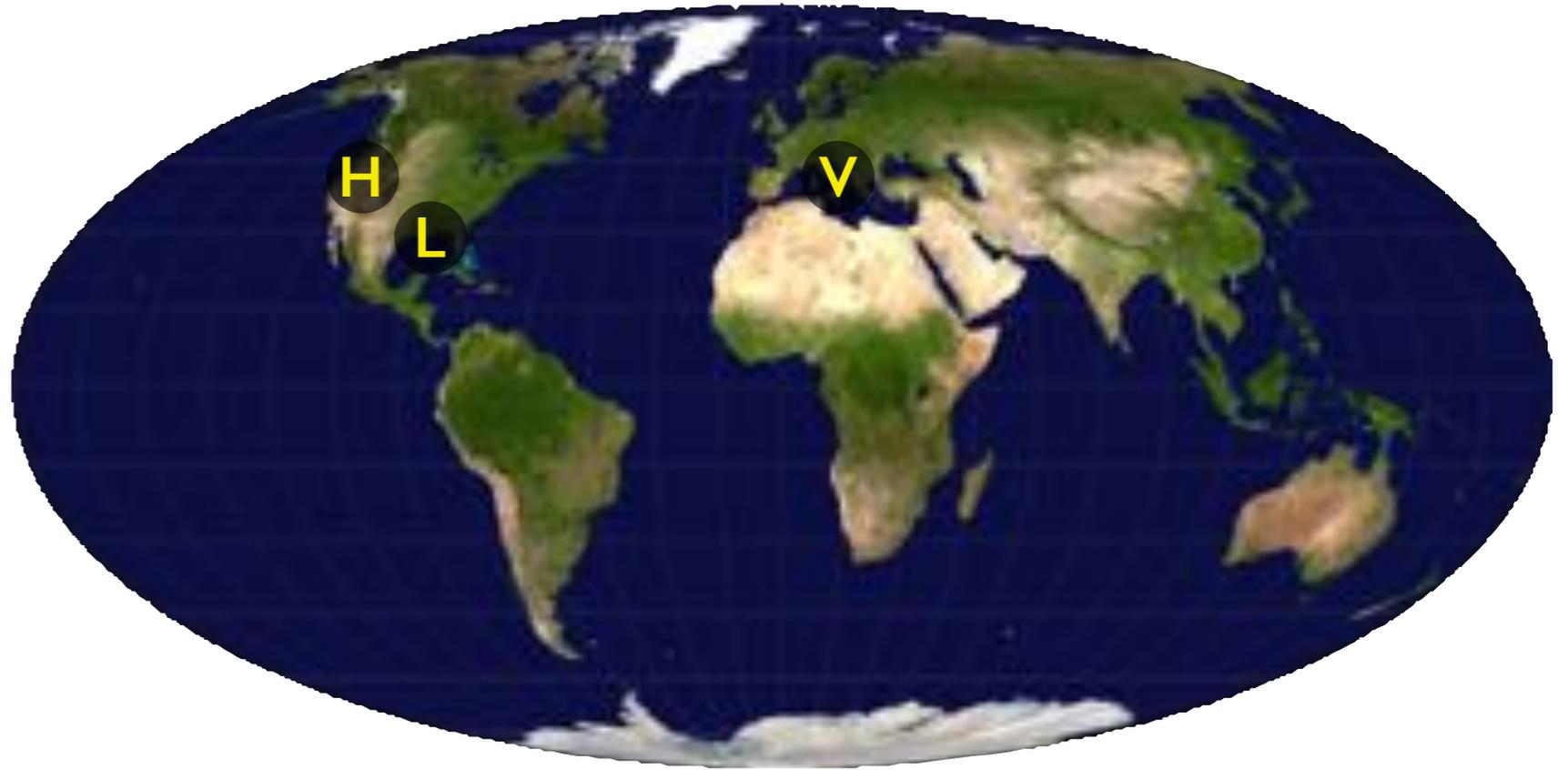
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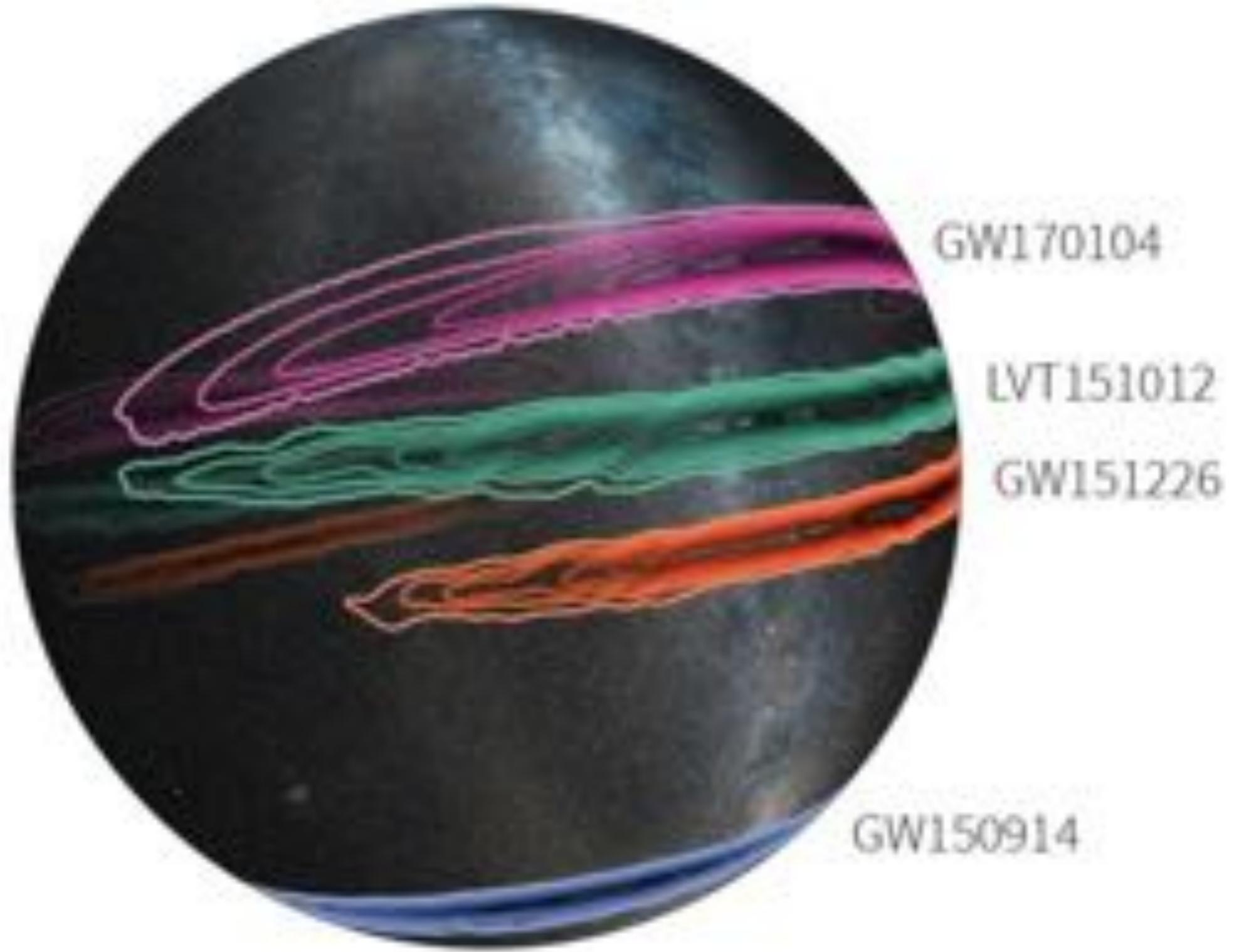


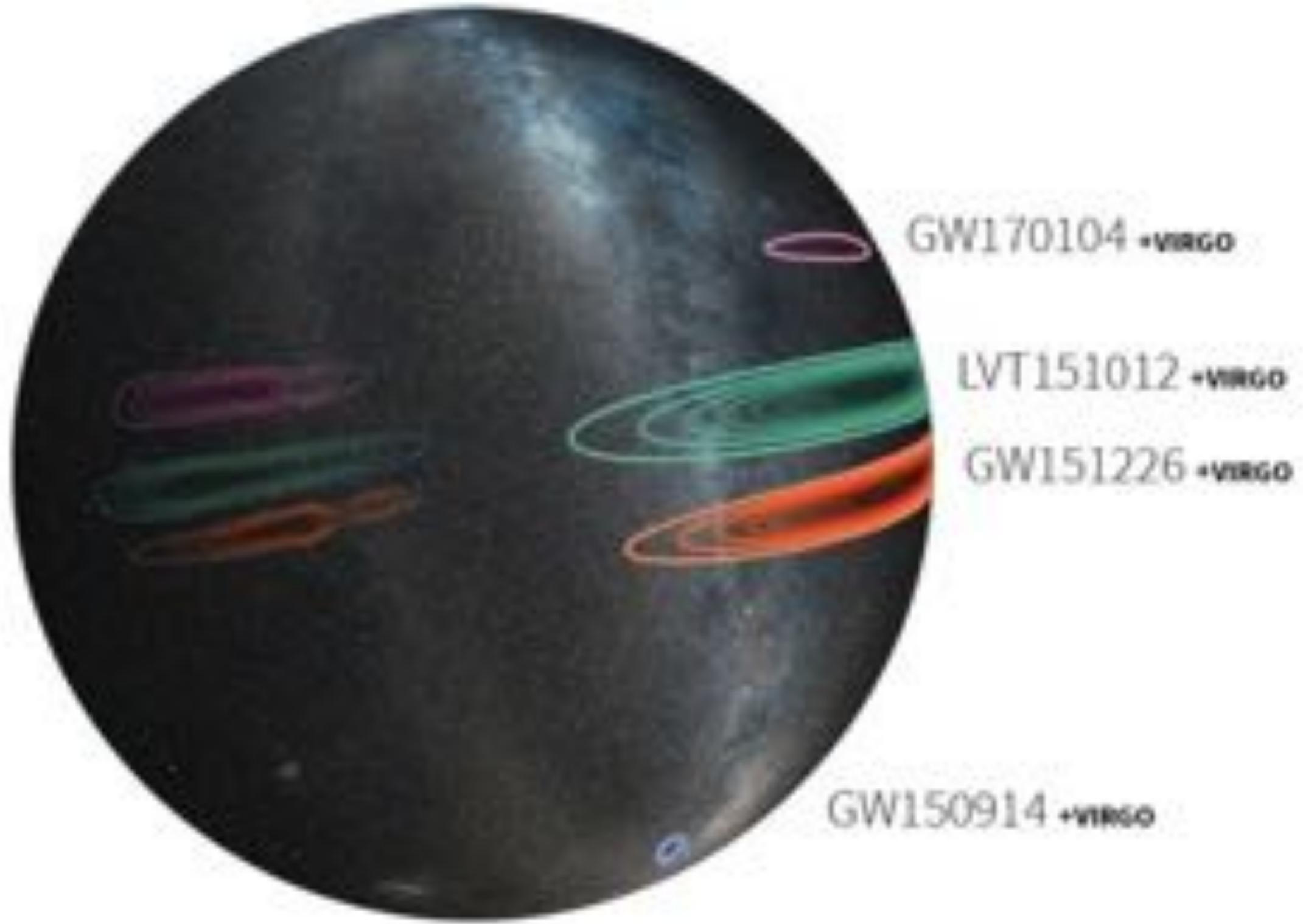


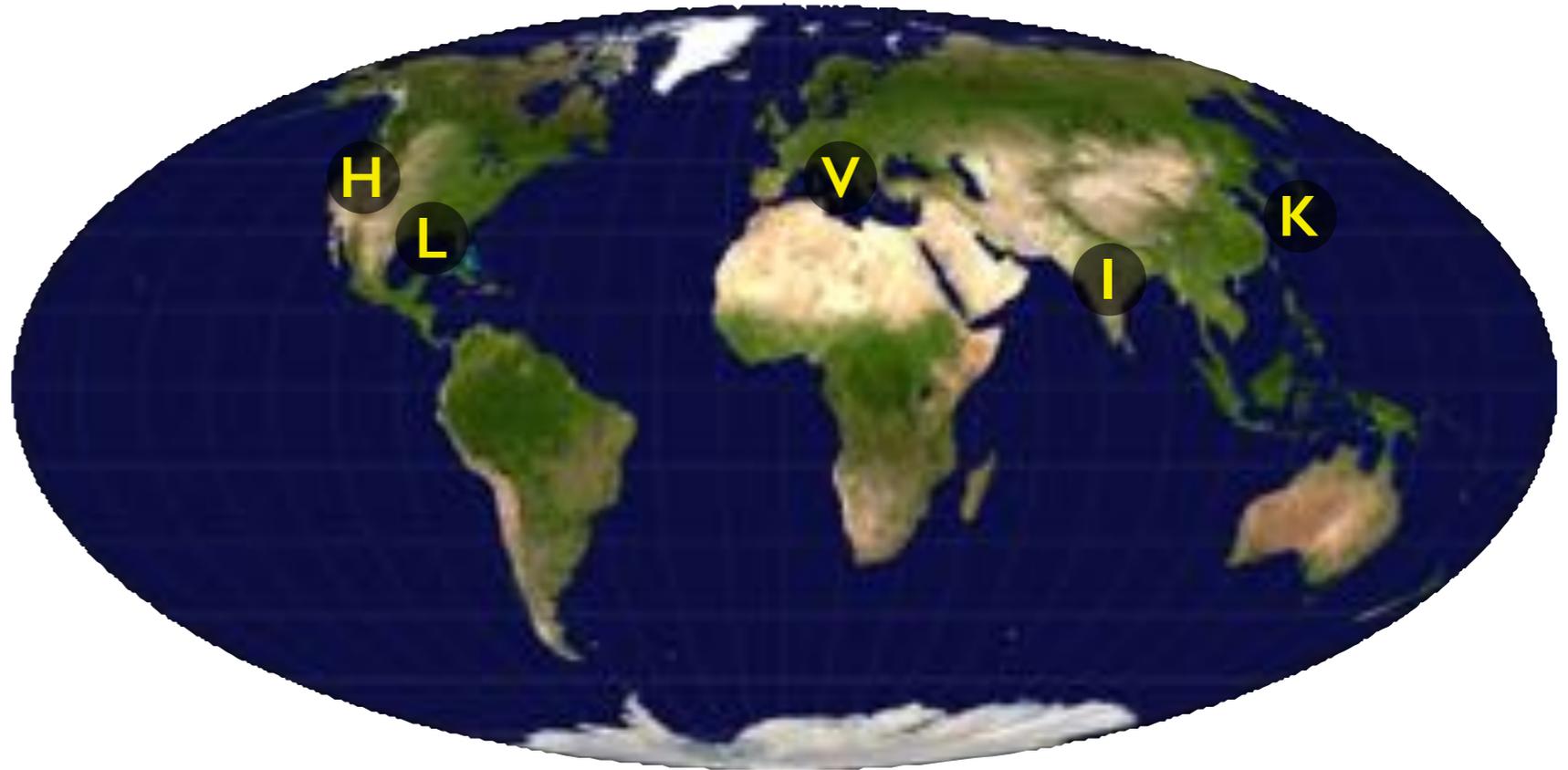












Gravity Spy + Classify - Zooniverse

Secure | <https://www.zooniverse.org/projects/zooniverse/gravity-spy/classify>

App | DWY10104\_CBOPE | NASA SPACE | WebTADS | NASA Travel | MJDG

Gravity Spy | About | Classify | Help | Collect | Run

LIGO has announced its first gravitational wave event! Look for a special tutorial when classifying in workflow. You might see a message about some Gravity Spy software that causes temporary issues with the tooling. We apologize for any inconvenience.

### Hanford

Frequency (Hz)

Time (s)

Normalized energy

Source	Frequency	Timing
1000 Line	Light Modulation	Repeating Wave
1400 Noise	Low Frequency Burst	Scattered Light
Air Compressor (60 Hz)	Low Frequency Line	Steady
My	None of the Above	Tone
Chop	No (GEO)	Multi-cycle waveform
Extremely Loud	Filtered Down	Wandering Line
Halls	Power Line (60 Hz)	Whistle
See Help		

Showing 20 of 22. 10 items shown

Classify | Done

Show the project tutorial

Restart the project introduction

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Gravity Spy | About | Classify | Help | Collect | Run

LIGO has announced its first gravitational wave event! Look for a special tutorial when classifying in workflow. You may find some Gravity Spy software that causes temporary issues with the tooling. We apologize for any inconvenience.

### Hanford

Frequency (Hz)

Time (s)

Normalized energy

Source	Frequency	Sound
1000 Line	Light Modulation	Repeating Wave
1400 Noise	Low Frequency Burst	Scattered Light
Air Compressor (50 Hz)	Low Frequency Line	Gravelly
My	None of the Above	Tones
Chop	No (GWS)	Multi-scale Harmonic
Extremely Loud	Filtered Dumps	Wandering Line
Halls	Power Line (60 Hz)	Whistle
Not Fish		

Showing 20 of 22. 10 items shown

Check & Save | Done

Show the project tutorial

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Gravity Spy + Classify - Zoom - A

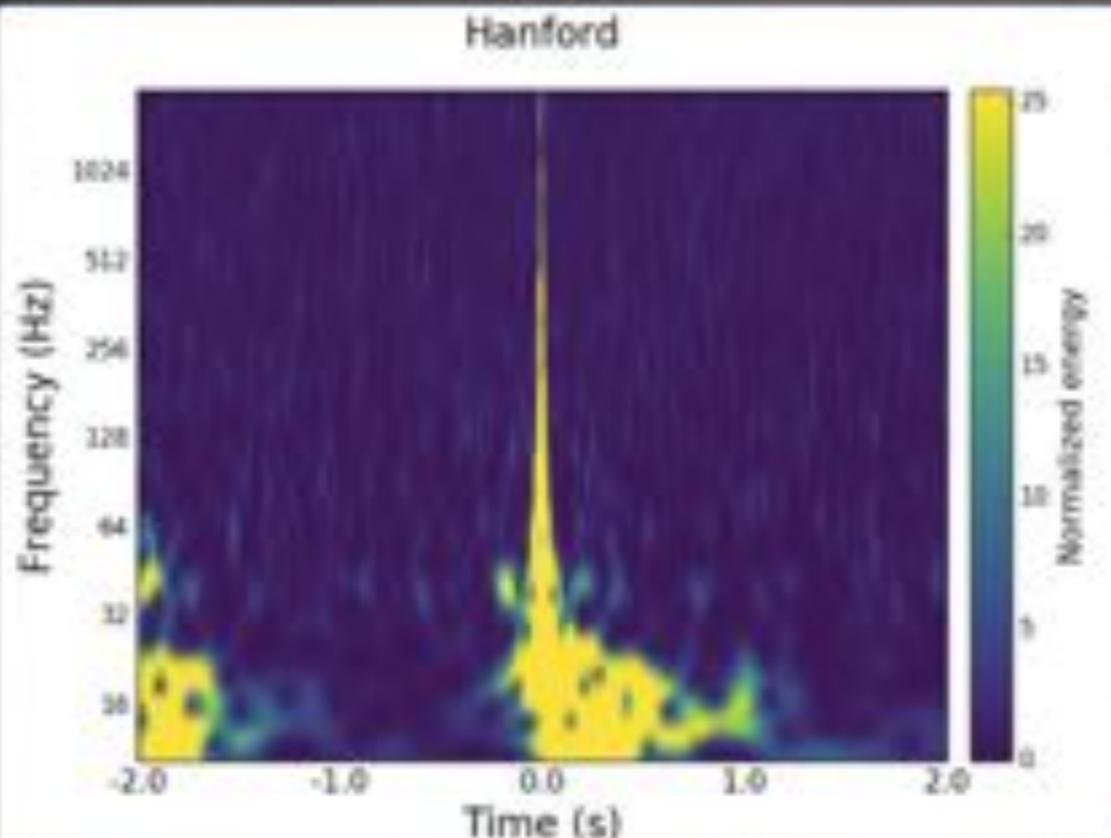
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App | DWY10104\_CBOPE | NASA SPACE | WebTADS | NASA Travel | MJDG

Home | About | Classify | Help | Collect | News

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### Hanford

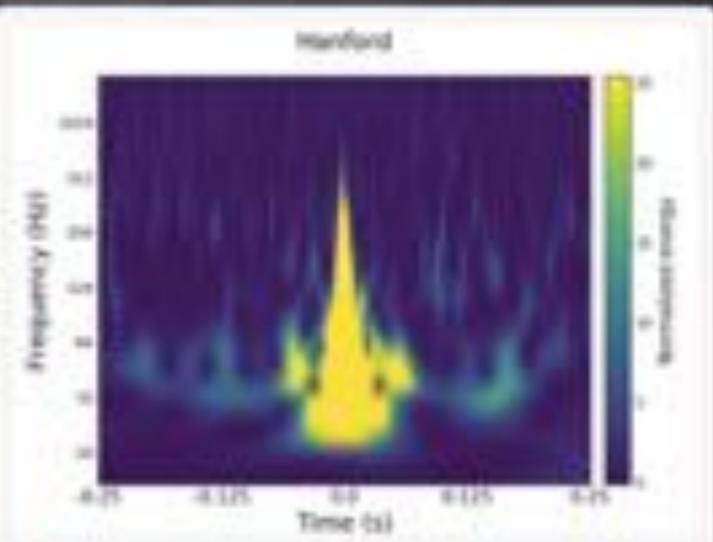


Frequency (Hz)

Time (s)

Normalized energy

### Hanford



Frequency (Hz)

Time (s)

Normalized energy

Real Fish

Real Fish are similar to like glaciers, but resemble a fish with a head, fins, and a tail.

How confident are you?  No  Some  Definitely not

Show the project tutorial

Restart the project introduction

FIELD GUIDE

Gravity Spy + Classify - Zooniverse

Secure | <https://www.zooniverse.org/projects/zooniverse/gravity-spy/classify>

App | DWY10104\_CBOPE | NASA SPACE | WebTADS | NASA Travel | MJDG

Gravity Spy | About | Classify | Tools | Collect | News

ZOO has announced its first gravitational wave event! Look for a special tutorial when classifying an waveform located 300 Mpc away and about 100 miles to the Gravity Spy software that cause temporary issues with the tooling. We apologize for any inconvenience.

### Hanford

Frequency (Hz)

Time (s)

Normalized energy

Source	Frequency	Setting
1000 Line	Light Modulation	Repeating Wave
1400 Noise	Low Frequency Burst	Scattered Light
Air Compressor (60 Hz)	Low Frequency Line	Gravity
My	None of the Above	Tone
Chop	No (GEO)	Multi-scale Harmonic
Extremely Loud	Filtered Down	Wandering Line
Walls	Power Line (60 Hz)	Whistle
<b>My Line</b>		

Showing 10 of 11. 11 items total

[Done & Talk](#) [Done](#)

Show the project tutorial

Refresh the project instructions

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Collections | Education | Daily Zooniverse |  
Build a Project | Our Team | Blog |  
How to Build | Publications

FIELD GUIDE

Gravity Spy + Classify - Zooniverse

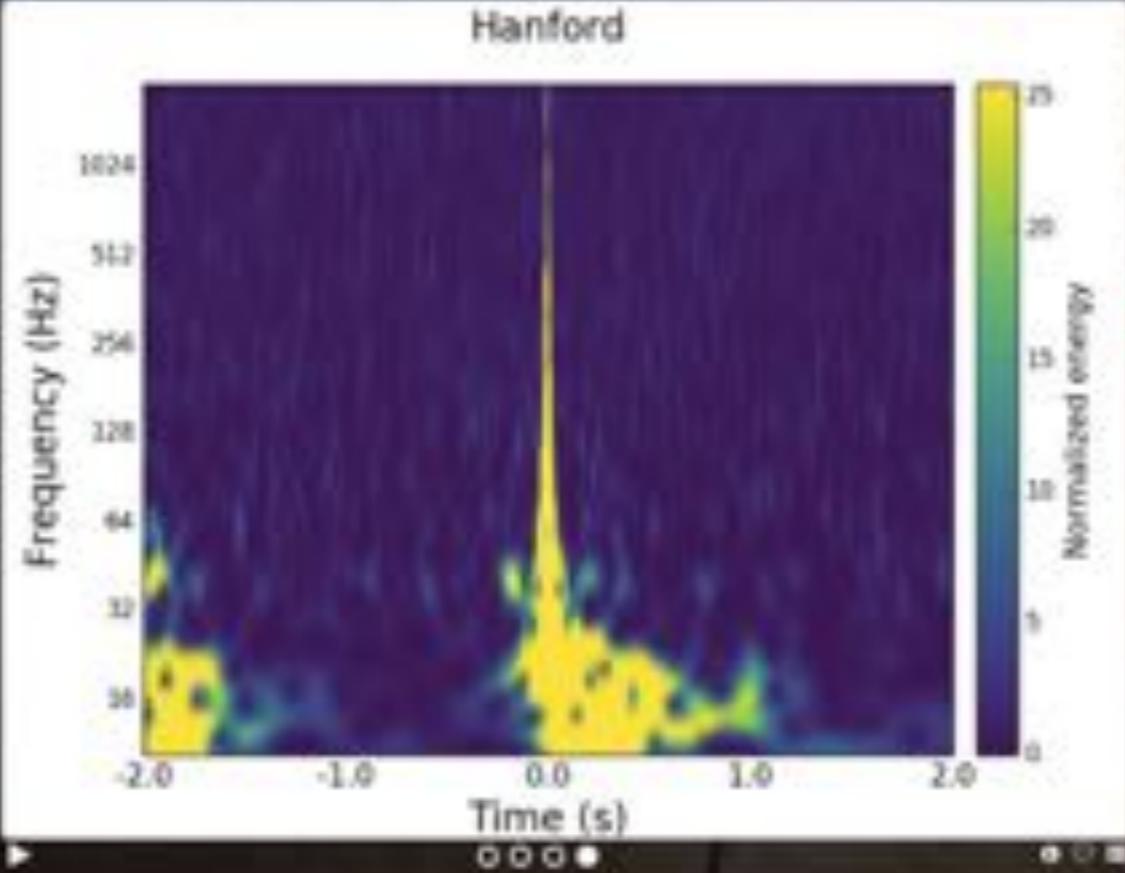
Secure | <https://www.zooniverse.org/projects/zooniverse/gravity-spy/classify>

App | DWY10104\_CBOPE | NASA SPACE | WebTADS | NASA Travel | MJDG

Gravity Spy | About | Classify | Help | Collect | Settings

LIGO has announced its first gravitational wave event! Look for a special tutorial when classifying in workflow! You may also notice Gravity Spy software may cause temporary issues with the tooling. We apologize for any inconvenience.

### Hanford



Frequency (Hz)

Time (s)

Normalized energy

You responded: Kit Fish

When our experts classified this image, they labeled it as a Light Modulation.

Some of the glitch classes can look quite similar, so please keep trying your best.

Check out the tutorial and the field guide for more guidance.

[Talk](#) [Help](#)

[View the project tutorial](#)

[Restart the project introduction](#)

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FIELD GUIDE



# Gravitational Wave Astronomy

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Tyson B. Littenberg

NASA/Marshall Space Flight Center

